DOCUMENTED
BRIEFING

Framework for Quantifying Uncertainty in Electric Ship Design

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PREFACE

The Office of Naval Research (ONR) has been sponsoring efforts to develop analytic tools for exploring both near- and far-term benefits of the electric-drive approach to naval propulsion. ONR tasked RAND National Defense Research Institute (NDRI), a unit of the RAND Corporation, to perform an initial assessment of one of the proposed approaches and to identify the needs for additional tools, assessments, and analysis. We developed a framework for assessing the relative benefits for ships of multiple technology types for each of the key components for electric propulsion (various motors, generators, power electronics, etc.). We did not analyze, however, specific technological alternatives. This work provides an approach that may be useful in making research and development applications.

This project was conducted in the Acquisition and Technology Policy Center of RAND National Defense Research Institute (NDRI). NDRI is a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, the unified commands, and the defense agencies.

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SUMMARY

This documented briefing outlines an approach for examining alternative technologies for electric ship design. We used quantitative methods for estimating the performance distribution of individual components and for integrating this information to obtain distributions of overall ship performance measures. To provide an example of the usefulness of these methods, we consider several component performance metrics for several components (motors, generators, power electronics, etc.) and examine their effects on one key ship-level performance metric, ship power density for a notional electric-propulsion destroyer. This framework features Monte Carlo simulation techniques.

ACKNOWLEDGMENTS

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Research Motivation and Objectives

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Develop a framework for quantifying uncertainty associated with new technologies for Navy ships. Specifically, the focus is on technologies associated with electric propulsion:

- Characterize and quantify the uncertainty in key electric-propulsion components with respect to certain performance metrics
  - Identify metrics or measures for gauging component and ship performance and assign probability distributions based on collected data.
- Translate uncertainty calculated for component technology performance into uncertainty with respect to ship-level performance via "Monte Carlo" techniques and a ship model.
- Utilize relatively simple and/or common software tools that can compute optimal sets of technologies given objectives/constraints that include cost, performance, and risk.

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This report describes a proposed framework for addressing uncertainty associated with new technologies for Navy ships. Specifically, the briefing addresses technologies associated with electric drives and electric ships. The Office of Naval Research asked the RAND Corporation to assist with the characterization and quantification of the uncertainty about the performance abilities of key electric-drive components.

To address the aforementioned request, RAND sought to identify a number of metrics (measures) for gauging both component and ship performance. We studied component technologies to develop notional models of these components, which captured the numeric ranges for some of the key metrics associated with these component types, such as weight and volume. Clearly, there will be uncertainty associated with these values.

To translate the uncertainty calculated for component technology performance into ship-level uncertainty, we used Monte Carlo techniques coupled with a RAND Electric-Drive Assessment Tool (REDAT) to develop a framework that facilitates consideration of both the variations among competing technologies in terms of component-level performance

metrics and the influence of certain technology choices on ship-level performance metrics. The framework implementation uses relatively simple and/or common software tools. It can be easily extended to solve for optimal sets of technologies given some objective, such as cost, performance, and/or measures of risk, and thus can serve the policymaker and R&D manager.

Outline

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- Electric-drive ships: motivations and components
- Decisionmaking under technological uncertainty
- Issues associated with quantifying uncertainty
- Framework for quantifying technological uncertainty
- Assessing ship-level uncertainties given component uncertainties via simulation
- Future work: concepts for using the framework to optimize an R&D portfolio
- Appendix A: the RAND Electric-Drive Assessment Tool (REDAT)
- Appendix B: Navy ship operating speed profiles

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This documented briefing begins with a discussion of why the Navy is considering the concept of an electric warship, as well as the technology options associated with such ships. Next is a discussion of decisionmaking under uncertainty as applied to weapon system development. We then survey the work of Timson (1968) and Kirby and Mavris (2001) and present issues associated with quantifying uncertainty for electric-propulsion component technologies. The focus is on quantifying uncertainty of electric motors, generators, and other key components for electric propulsion, given limited data.

RAND developed an analytic framework to facilitate the assessment of uncertainties in performance of ship component technologies and to translate these component-level uncertainties into ship-level performance uncertainties. As an example of how this framework can be implemented, we present preliminary results on how propulsion-motor uncertainties affect ship-level performance measured by displacement and fuel consumption. This framework is amenable to being used with an optimizer, so the best technology set can be selected, factoring in uncertainty in component performance, cost, and development time.

Appendix A describes REDAT, which facilitates the calculation of ship performance (displacement, fuel consumption, power density, etc.), given operating conditions and technology choices as inputs. Appendix B discusses ship operating profile data.

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Electric-Drive Ships: Motivations and Components

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This section discusses the motivation for utilizing electric-drive propulsion and the need for all-electric ships. Proponents of electric propulsion see an opportunity to improve mission performance, including improving survivability and affordability. But the concept of an electric ship, and specifically electric propulsion, comes with a certain amount of risk. The risk associated with an electric ship is related to the risk associated with the key components that make up an electric ship.

The components an electric ship requires are electric motors, electric generators, power electronic switching devices, and advanced propulsor concepts, among other items. Generally speaking, most of the technology options (e.g., the type of electric motor) are not well proven in the sizes a Navy ship would require. There are different technology options for all the major components. Research and development (R&D) programs to develop any of the technology options for any of the components are expensive. Development efforts for a single motor technology type can cost on the order of $100 million.[1] Identifying the right set of components

[1] "Navy Wrestles with Prospects, Price for Electric Drive for Subs, Ships" (1999).

and component technologies, one that is feasible and practical, to invest in and commit to is a challenge.

Why Does the Navy Want an Electric Ship?

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- **Improved mission performance**
  - **Increase ship power density**
  - **Enable advanced weapon and propulsion concepts**
- **Improved survivability**
  - **Better stealth**
- **Improved affordability**
  - **Design flexibility & fuel efficiency**

Ship Design Goals

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A transition to electric propulsion could provide the Navy with a host of benefits and opportunities. A key argument in favor of this concept is that electric ships can facilitate a naval force that is superior in a number of areas, including (1) mission performance; (2) survivability; and (3) affordability (Weldon et al., 2002), where affordability refers to through life cost.

Among the more-specific potential benefits that proponents cite are reduced size, the configuration flexibility of the propulsion architecture, signature reduction, a suitable power source for new high- and pulse-power weapons, fuel efficiency, and lower maintenance (see Doyle, 1977; Boylston and Brooks, 2001; and Doyle et al., 1980).

A Superior Naval Force Requires Innovation

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Requirements:

- Superior Survivability
  - Longer range, higher resolution sensing
  - More effective self-defense
  - Improved speed and endurance
  - Improved fight through capability
  - Reduced signatures and vulnerability
- Superior Affordability
  - Use of COTS, updatable platforms, reduced workload
- Superior mission performance
  - Higher rates of fire, deeper magazines
  - Shorter weapon time of flight
  - Increased weapons range
  - Improved long-range sensing
  - Improved support for forces ashore
  - Reduced cost per kill
  - Higher sortie generation rates
  - Superior range, loiter capability, maneuverability
  - Electric power available for future

Proponents: Electric Ships Facilitate Innovation

Source: Roadmap to an Electric Naval Force, Naval Research Advisory Committee Report, July, 2002, pp.14-15

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It is important to consider the specifics of how electric-ship technologies can provide survivability, mission performance, and affordability superior to those of conventional Navy architectures. The Naval Research Advisory Committee report (Weldon et al., 2002) described some of the supposed advantages as follows.

A superior naval force is one imbued with superior mission performance, superior survivability, and affordability. Specific characteristics of superior mission performance include (1) deeper magazines, (2) higher rates of fire, (3) shorter weapon flight times, (4) increased weapon range, (5) improved long-range sensing, (6) improved support for forces ashore, (7) improved mobility, (8) higher sortie-generation rates, (9) more-effective land-combat vehicles, and (10) reduced cost per kill.

The specific characteristics of superior survivability are (1) longer range, (2) higher-resolution sensing, (3) more-effective self-defense, (4) improved speed and endurance, (5) improved fight-through capability, and (6) reduced signatures and vulnerability.

The specific characteristics of superior affordability include (1) the use of commercial-off-the-shelf (COTS) components and technology,

(2) updatable platforms, and (3) reduced workloads. In general, commercial synergism is an important characteristic for improving affordability (Rushworth, 2003).

Key Concepts/Technologies Underlying the Requirements

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- •Superior survivability
  - High-power microwave applications
  - Dynamic armor and laser weapons
  - Electrically reconfigurable and redundant systems
  - Very low acoustic and thermal signatures at low power
- •Superior mission performance
  - Electromagnetic guns and launchers
  - High-power, high-resolution sensors
  - Wireless power transmission
- •Superior affordability
  - Flexible, real-time power allocation
  - Increased automation and commonality are affordable warfighting upgrades
  - Lower maintenance
  - Superior fuel economy

Source: Weldon et al. (2002), pp.14–15.

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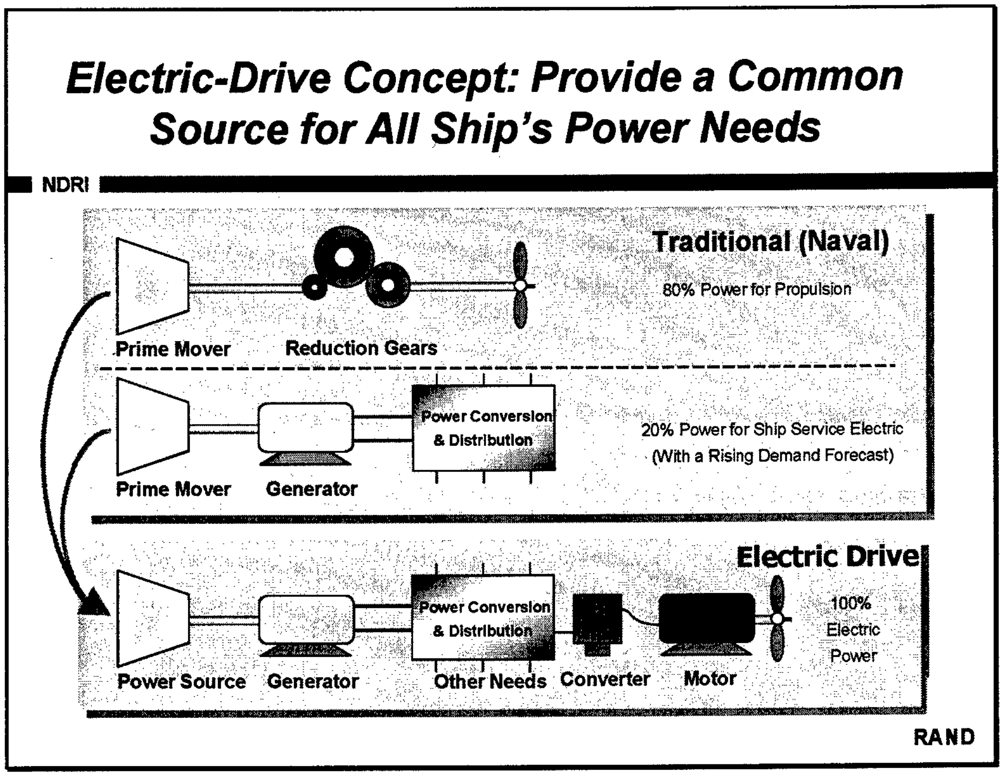
A ship that can produce a large amount of electric power can facilitate a number of specific technologies that provide bases for achieving the performance improvements described above. This slide describes the specifics of how electric ship technologies can lead to survivability, superior mission performance, and affordability superior to those of conventional navy architectures.

For example, research is ongoing into the possibility of using electromagnetic railguns as successors to the existing electrochemical guns on existing warships. A railgun accelerates a small projectile (1–3 kg) to high speeds (2.5–3.5 km/second) that could produce a range of 300–400 nautical miles (Feliciano, 2002). Two major benefits of electromagnetic railguns are that (1) they could eliminate the need to store dangerous explosive devices onboard, which ignite if the ship is hit, and (2) the use of railguns could decrease the amount of space required on the ship for ammunition by using small projectiles instead of large shells. More-traditional electronic systems, such as radar, continue to present increased power needs, which proponents claim electric drive can provide more efficiently.

Energy storage and shipboard power availability are two potential roadblocks to this technology. Advanced electric-propulsion concepts could address these roadblocks. While electric drive can facilitate such concepts as railguns, railguns also have other technical challenges that this report does not address.



The traditional (mechanical drive) power architecture of Navy ships differs from that of an electric-drive architecture. Traditional architectures provide at least two separate power systems. Main propulsion provides about 80 percent of all power for a typical ship; this goes to its propulsion and nothing else. The ship's service generators meet the other 20 percent of the ship's needs, in the form of electricity. In contrast, an electric-drive architecture provides all ship's power, in the form of electricity, for any need. Thus, electric-drive power systems unite the traditionally separate power sources.

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Decisionmaking Under Technological Uncertainty

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This section surveys a few relevant studies that address decisionmaking under technological uncertainty. Many technological choices are available for the components that make up an electric-propulsion device. Thus, the choices of technologies that underlie these concepts are critical for evaluating the overall concept. Because of the R&D costs involved, it is only possible to pursue a limited subset of these technology options.

Early Work on System Development Decisionmaking Under Technological Uncertainty Utilized Subjective Probabilities

NDRI

Key premises in measuring technical performance in complex systems (Timson, 1968):

1. **Progress is characterized by reduction in uncertainty**
2. **Assessment of uncertainty relative to development is subjective**
3. **Subjective estimates of uncertainty can be expressed in terms of probabilities**
4. **The amount of uncertainty is indicated by statistical measures**

RAND

Early RAND work (Timson, 1968) explored approaches to decisionmaking for weapon system development given technological uncertainty. According to the abstract for Timson (1968), this work developed a

> procedure for measuring the status and progress of a complex system development program. The procedure is based on four premises: (1) Progress is characterized by reduction of uncertainty; hence, if uncertainty can be measured at different times, progress can be indicated by changes in measures of uncertainty. (2) Assessment of uncertainty relative to development is subjective. (3) Subjective estimates of uncertainty can be expressed in terms of probabilities. (4) The amount of uncertainty is indicated by statistical measures of appropriate probability distributions. Consistent with these premises, the procedure for obtaining probability distributions for critical system performance characteristics involves five steps: (1) Obtain design equations. (2) Determine subjective probabilities. (3) Generate probability distributions for system performance. (4) Calculate statistical measures. (5) Compare measures at different times to obtain indications of progress.

Techniques for Analyzing the Effects of Alternative Engineering Decisionmaking Policies for System Development Projects

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Dynamic technical risk assessment incorporates (Timson, 1970):

1. **The relationship between the characteristics of components, subsystems, and the total system, and**

2. **The values of component, subsystem, and system characteristics**

RAND

Timson (1970) explored approaches to risk analysis. He proposed "a technique for analyzing the effects of alternative engineering decisionmaking policies and alternative forms of military system development contracts." Timson observed that development projects are characterized by goals set by a number of factors, including states of knowledge about (1) the relationship between the characteristics of components, subsystems, and the total system and (2) the values of component, subsystem, and system characteristics. The procedure Timson presented is a dynamic technical risk assessment that incorporates data from specific engineering tests to reveal probability distributions of characteristics. Propagation-of-error methods served to determine the effects of the component-level forecast on the overall system and program.

The TIES Methodology Is an Example of an Approach for Selecting Among Competing Ship-Component Technologies

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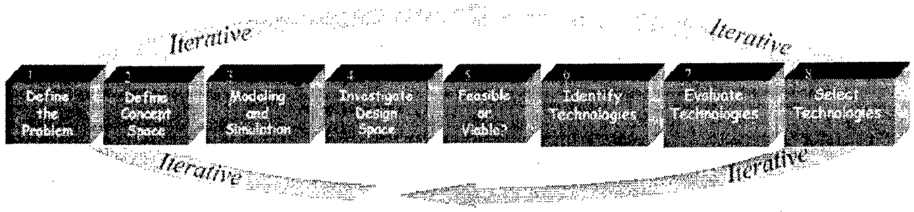

Steps for the Technology, Identification, Evaluation, and Selection Method (TIES) for design of complex systems as applied to ships

1. **Identify ship needs**
2. **Develop physics-based model to represent generic technologies**
3. **Evaluate technology concepts and their effects on ship performance**
4. **Select those that are beneficial to a given set of design objectives**

RAND

This slide describes the TIES method, which borrows from Timson's concepts and is one potential framework for addressing the issue of technology selection for Navy ships. The goal of TIES is to provide high-level decisionmakers with a tool for quickly triaging multiple choices for complex systems, i.e., to simplify the complex. TIES requires numerous simulations of ship performance so that a meta-model can be developed using a set of simple parameters that fairly represents the performance space of the ship and, when input to TIES, will give accurate performance predictions for each combination of choices. Quoting Kirby and Mavris (2001), p. 2:

> The development of TIES focused on the application of a set of technologies for a single vehicle concept and the identification of the highest payoff technology combinations within that set. The method is an eight step process . . . which begins with defining the problem, in terms of the customer requirements that drive the product design, to selecting the best family alternatives, in terms of design attributes and technology sets, that best satisfies the customer requirements.

Kirby and Mavris (2001) and Roth and Mavris (2002) are key references describing this method.

TIES is one example of a framework or methodology for permitting a decisionmaker to assess technologically and economically feasible and viable alternatives using the performance criteria he or she has selected and defined. A key requirement for making such a framework useful is incorporating uncertainty and risk as design factors arise in pursuing novel technologies. A deterministic approach is inadequate and may be misleading. The goal is to provide a decisionmaker with a quantitative measure of the likelihood of attaining the specific metric value and allow him or her to take action according to his or her risk tolerance. Furthermore, a physics-based model of ship-level effects is crucial because of the complex nature of ship design. In a later section of this documented briefing, a description of an alternative, Excel-based framework is provided that achieves what the TIES framework purports to provide.

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Issues Associated with Quantifying Uncertainty

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This section describes issues associated with quantifying uncertainty when data are available but limited. This is an important but difficult step; determining component metric uncertainties is nontrivial. The estimates we present below are based on the maturity of the key electric-drive components.

The Challenge: How to Quantify Future Performance Uncertainty in Evolving Component Technologies

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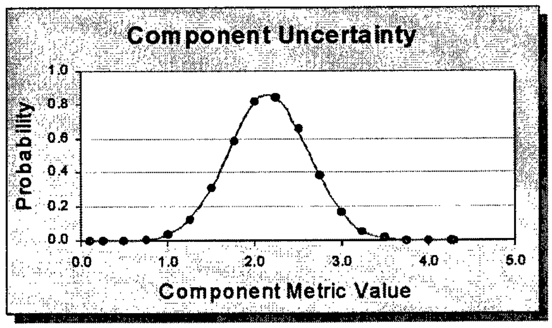

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A key challenge is quantifying future performance uncertainty in evolving combinations of electric-drive component technologies with limited data sets. We did collect some technical information and used probabilistic techniques to determine the uncertainties associated with individual electric-drive components (or combinations of components). As we will show, probabilistic modeling along with simple and intuitive assumptions can be used to structure the data.

Available Data Are Used to Address Key Aspects of Applying a Technology Selection Process

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- Identify appropriate set of technology metrics for ship and components
- Create functional relationships between constraints and technology metrics
- Assign probability distributions to the technology metrics

RAND

We gathered technical information on electric-drive ship components and used probabilistic techniques to assess the data (which came from open sources; more current information may require using proprietary information).

An important step in using this or any other data set is to identify the important performance metrics and constraints. RAND characterized the uncertainty in the achievable component performance on a set of specified performance metrics (e.g., the power density of a motor, generator, and power electronics). Many other metrics are of interest—in particular, those that involve cost. However, for the sake of brevity, we explore only a few key metrics here. We modeled uncertainty by specifying probability distributions that reflect the low, best, and high estimates of the metrics from the data. Subsequent slides will further explain uncertainty modeling.

Uncertainty in R&D Has Multiple Sources and Multiple Ways to Characterize

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- **Development risk has many sources**
  - Basic technical issues (i.e., can it be built?)
  - Achieving required performance/metrics
  - System integration
  - Cost and development time
- **Each source of uncertainty can be characterized differently**
  - Distribution around a best estimate
  - Probability of success (binary: yes or no)

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Uncertainty in R&D management can be associated with a number of sources or questions, including (1) whether or not research will be able to solve the large problems necessary to build a full-scale prototype, (2) what performance ranges the technology can provide, and (3) whether or not integration of the component into the larger system will be successful. Clearly, the characterization of technological uncertainty is nontrivial.

Determining Component Metric Uncertainties Is Nontrivial

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Many component types are needed, each with multiple alternative technologies and metrics

- Example: Electric Motor
  - Motor technologies:
    1. Synchronous
       - Conventional
       - Permanent magnet synchronous
       - High-temperature superconducting
    2. Induction
    3. Homopolar (DC, HTS)
       - High-temperature superconducting
  - Motor component metrics
    - Power per unit weight (MW/kg), or
    - Power per unit volume (MW/m^3)
    - Development costs ($/kg)

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Synthesizing component-level performance metrics is complex. As a specific example, we consider propulsion motors. Motor technologies can be put into three general categories (synchronous, induction, and homopolar). Such metrics as the power density (which we define here as a ratio of maximum motor power rating to the motor's weight) can characterize motor performance. Other metrics include the ratio of power to volume and torque density.

The Navy once planned to build a class of 17,000-ton destroyers, the DD-21, that would use electric propulsion.[2] By late 2001, the Navy had renamed the program to DD(X) and pledged to revisit key requirements for the ship. Recent reports ("Young Seeks Smaller DD[X] Ship, Prompting Fire Support Discussions," 2003) suggest that a 13,000-ton destroyer is now under consideration. If electric propulsion is to remain for this relatively smaller destroyer, the weight and volume of the electric motor will be key. Furthermore, the power-to-weight ratio, power-to-volume ratio, torque density, and other measures will depend heavily on the type

[2] "Young Seeks Smaller DD(X) Ship, Prompting Fire Support Discussions" (2003).

of electric motor. In-hull permanent magnet synchronous motors and advanced induction motors are among the technological options (Naval Technology, undated). The table below provides two examples of useful data for motors. Power per unit weight is shown for the synchronous motor used on the *Queen Elizabeth 2* (QEII), as well as the Alstom Integrated Power System (IPS) Induction motor. American Superconductor has built a 5-MW High-Temperature Superconductor (HTS) synchronous motor that weighs 26,000 kg and occupies 20 cubic meters, which is better in terms of power density than the examples listed below (Ryan, 2003).

Name	Power (MW)	Weight (kg)	Torque (ft-lbs × 10^6)	Power-to-Weight Ratio (kW/kg)	Torque-Density (ft-lbs per kg)	Volumetric Power Density (MW per m^3)
QEII synchronous motor	44	285,000	2.15	0.15	7.5	0.1
IPS advanced induction motor	19	121,000	0.89	0.16	7.4	0.2

SOURCE: Simmons et al. (1994).

Simmons et al. (1991) cite design studies suggesting that 1 kW/kg is an upper bound for power density,[3] perhaps only achievable with superconducting motors. As the table suggests, existing motors have not demonstrated such a power-to-weight ratio. American Superconductor also has a $70 million contract to build and deliver a 36.5-MW HTS synchronous motor. Existing specifications for that design suggest a power-to-weight ratio of approximately 0.5 kW per kg, including weight or rotor, armature, frame, and cooling devices (Karon, 2003).

Besides motors, there are quite a few other component types (each with its own set of possible choices), and system interactions between the components make this problem complex.

[3]Note that this report specifies power alternatively in terms of kilowatts (kW), megawatts (MW), and horsepower (hp) to specify power; 1 hp equals 0.74567 kW.

Existing Estimates for Maturity of Key Components Is Useful for Capturing Probability of Success

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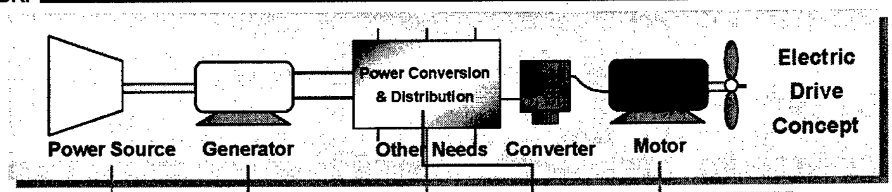

POWER SOURCE

Technology	Status
Diesel Engine	G
Conventional Gas Turbine	G
Advanced Gas Turbine	Y
Fuel Cells	R

GENERATOR

Technology	Status
Induction	Y
Synchronous	G
Permanent Magnet	R
HTS Synchronous	R
HTS Homopolar	R

DISTRIBUTION

Technology	Status
DC Architecture	G
DC Breakers	Y
AC Supercond. Trfm.	Y
Supercond. Conductors	R
Insulation	Y
Insulation High Power Density	Y

MOTORS

Technology	Status
Induction	R
Synchronous	G
Permanent Magnet	R
HTS Synchronous	R
HTS Homopolar	Y

CONDITIONING

Technology	Status
Insulated Gate Bi-Polar Transistors	G
MOS Controlled Thyristor	R
MOSFET Turn-Off Semiconductor	R
PEBB	Y
Power Density	R
High Power Levels	R

NOMENCLATURE

R Further Technology Development Required

Y Technology Generally Well Understood but Affordability and Scaling to Ship Power Levels Requires Development and Demonstration

G Technology Ready Near Term to Support Ship Design Development Studies

Source: Jebsen, 2001

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This slide presents a partial listing of the basic technology alternatives for each component (power source, generator, power electronics, electric motor, and propulsor) in the electric-drive system. The slide also provides subjective evaluations of the comparative technological readiness of individual technology concepts, which we based on a prior study (Jebsen, 2001). The indications are that a number of component technologies require further development.

The power source is usually a gas turbine engine or diesel engine that transforms the propulsion fuel's chemical energy into mechanical energy. A generator then converts this mechanical energy into electrical energy.[4] Power electronic devices condition and distribute power throughout the ship. The electric motor is the major consumer of this power[5] because it enables the propulsor (the device that imparts energy to propel the ship).

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[4]A generator would not be necessary if the prime mover were a fuel cell. However, a fuel cell is more likely to be an auxiliary power source.

[5]Power to the electric motor must be conditioned so that its speed and torque can be controlled. Devices for this purpose are called *motor drives, power converters,* or *power controllers.*

The propeller can be podded so that it extends into the water, away from the ship's hull.

A Framework for Quantifying Technological Uncertainty

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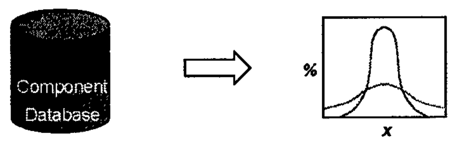

1. **Quantify the uncertainty in achieving performance for the major components**

2. **Use simulation and REDAT deterministic calculations to assess ship goal uncertainties using component uncertainties**

RAND

This section describes a methodology used to quantify performance under uncertainty and explains how technical information on electric-drive ship components, collected from various sources, can be used with probabilistic techniques to quantify and analyze technological uncertainty.

Uncertainty analysis can help structure what we know. For the sizes and power ratings required for Navy ships, not many data points are available for the various components that support electric propulsion. Although it is usually better to have more data (i.e., more prototypes and full-scale demonstrations of various technological options for various components), time and resources do not often afford this luxury. However, probabilistic modeling, along with simple and intuitive assumptions, can structure smaller data sets. For example, greater variance in the estimates reflects greater uncertainty. Low, best, and high estimates bound and define probability distributions.

1st Step: Quantify the Uncertainty in Achieving Performance for the Major Components

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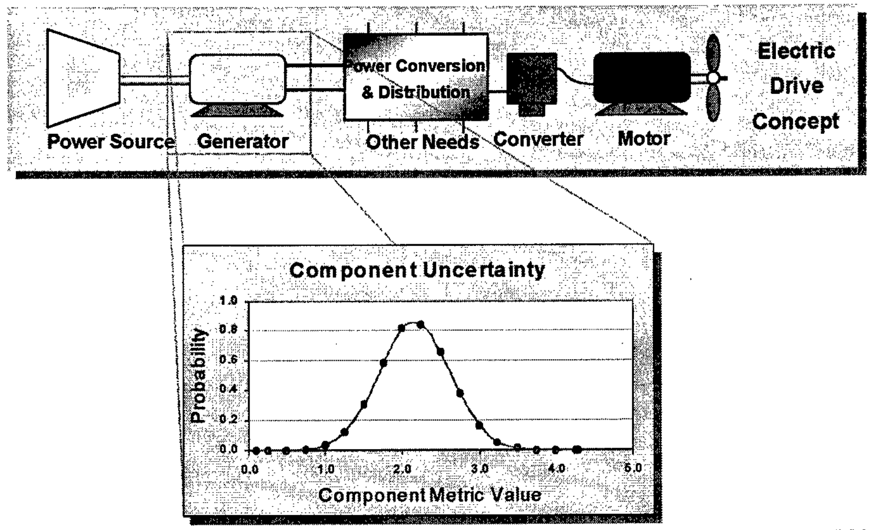

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This slide summarizes our approach for quantifying component technology uncertainty. For each electric-drive component technology, we constructed a probability distribution function for each of the metrics characterizing the technology, using the methodology detailed below.

Need a Distribution to Capture Minimum, Maximum, and Most-Likely Values for Component Performance

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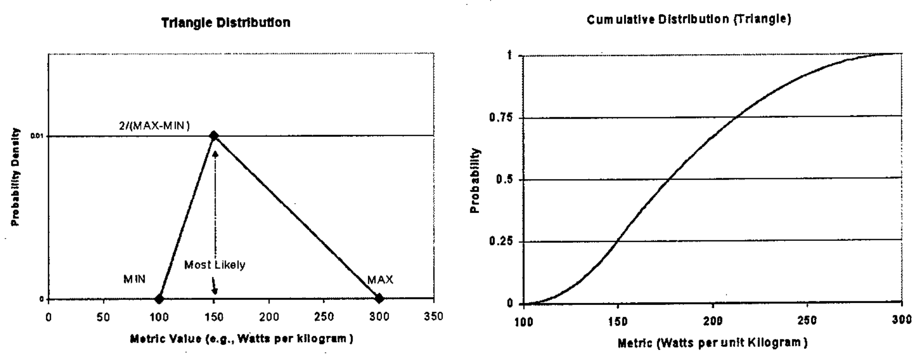

Triangle distribution captures these

RAND

As an example, the slide describes a simple probability distribution, the triangle distribution. The parameters of the triangle distribution are (1) maximum value, (2) minimum value, and (3) most-likely value. Some suggest the triangle as a useful way to summarize a survey of expert opinion. However, it may not weigh the most-likely value in terms of its mean value. The mean for a triangle distribution is

$$(\text{max} + \text{min} + \text{most\_likely})/3 .$$

The drawbacks of this distribution are that the maximum and minimum value are allowed to be as influential on the mean as the most-likely value and that the minimum, maximum, and modal value of a distribution capture only limited information. For example, one can describe an infinite family of distributions that have the same values for these quantities.

Another similar distribution, and an alternative, is the BetaPERT distribution, which can be arrived at with some manipulation of the Beta distribution. We describe this next.

Need a Distribution to Capture Minimum, Maximum, and Most-Likely Valued for Component Performance (concluded)

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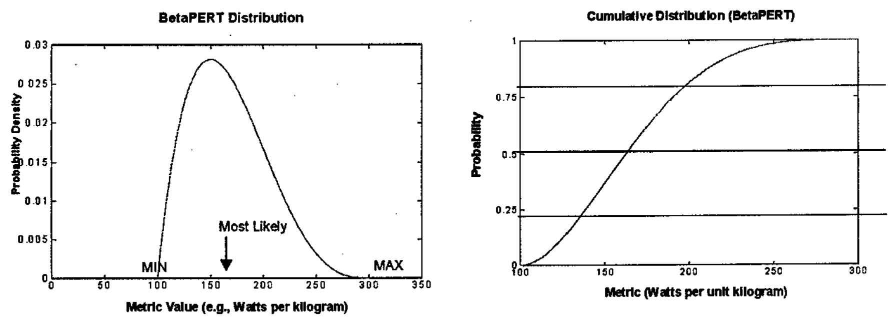


BetaPERT distribution captures these better

RAND

The BetaPERT distribution is a more useful probability distribution. It can be arrived at with some manipulation of the Beta distribution, and it represents expert opinion more realistically (Vose, 2000, p. 275). This distribution, which Vose calls *BetaPERT*, has a mean value of (max + min + 4 × most_likely)/6:

> The mean for the BetaPERT distribution is far more sensitive to the most likely value and correspondingly less sensitive to the minimum and maximum values than the mean of the triangle distribution. Therefore, it does not suffer to the same extent the potential systematic bias problems of the triangle distribution in producing too large a value for the mean risk analysis results. (Vose, 2000, p. 271.)

Although we used the BetaPERT for all the technologies we examined, future work might consider different distributions for different technologies with different maturities.

Minimum, Maximum, and Most-Likely Values Determine Shape Parameters for BetaPERT Distribution

NDRI

- **Characterized by three inputs (PERT)**
  - a – minimum value
  - m – most likely value
  - b – maximum value
- **Related to Beta distribution**
  - Shape parameters determined by inputs

$$\mu = \frac{a + 4 \times m + b}{6}$$

$$\alpha_1 = 6\left(\frac{\mu - a}{b - a}\right)$$

$$\alpha_2 = 6\left(\frac{b - \mu}{b - a}\right)$$

PDF: $$f(x) = \frac{(x - a)^{\alpha_1 - 1}(b - x)^{\alpha_2 - 1}}{B(\alpha_1, \alpha_2)(b - a)^{\alpha_1 + \alpha_2 - 1}}$$

$$a < x < b$$

CDF: $$F(x) = I_z(\alpha_1, \alpha_2),\ z = \frac{x - a}{c - a}$$

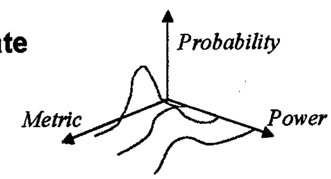
RAND

The BetaPERT distribution combines the Beta distribution and the Project Evaluation and Review Technique (PERT). Three characterizing inputs are required: a minimum value (a), a most-likely value (m), and a maximum value (b) of the random variable. These inputs determine Beta distribution shape parameters (alpha1 and alpha2). The closed-form equations for the probability density and the cumulative density functions (CDFs) depend on inputs and shape parameters. The CDF for BetaPERT distribution is the incomplete Beta function. Note that, in the above equation, $B(\alpha_1, \alpha_2)$ is the Beta function.

Steps Being Utilized to Characterize the Uncertainty from Data

NDRI

1. **Determine low, best, and high estimate**
   - **Envelop method**



2. **Fit statistical distribution**
   - **e.g., BetaPERT**
3. **Use conservative assumptions**
4. **Apply greater uncertainty to less mature technologies**
5. **Confirm analysis matches intuition**

RAND

In general, we determined the best estimate by regressing the data on a common component metric (e.g., motor size). The high and low values bound the range of uncertainty in the best estimate for each motor size. The envelope method is one procedure for bounding this range. We modeled the uncertainty in motor performance using these three data points (i.e., the low, best, and high estimates) as parameters in a BetaPERT distribution. The next slide provides details about how we applied the envelope method.

While applying this method, we adhered to three principles. First, the minimum performance is defined by the lowest elicited performance. This ensured that the estimate of the performance attainable for each component would be conservative.

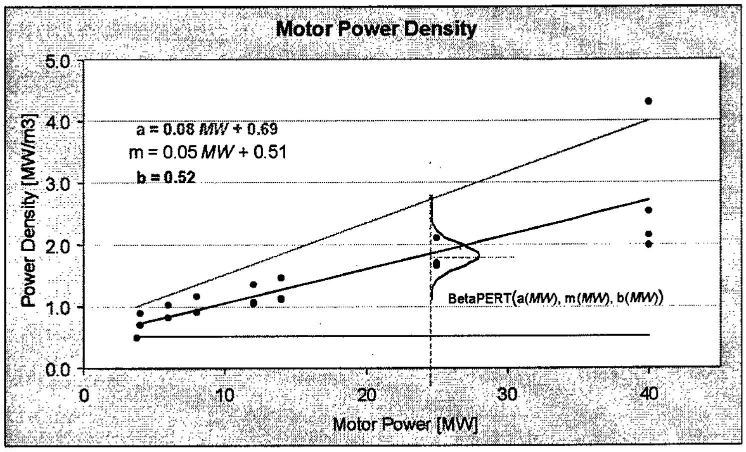
Second, uncertainty does not decrease as motor size increases.[6] This is intuitive; one would expect greater uncertainty in technologies that have not yet been built (e.g., larger motors). Finally, envelopes selected and best-fit lines (for best estimates) should not conflict with intuition.

---

[6]We believe that it is unclear whether it is possible to build an electric motor for the Navy that would be much higher powered than the electric motor that is already commercially available.

Data Surveyed Provide Low and High Estimates at a Number of Power Ratings

NDRI



Metric ranges synthesized as a function of power

RAND

This slide depicts the method we applied for capturing electric motor performance (or any other metric) as a function of motor power rating. This method is suitable for any component. The three steps are as follows:

1. Using a scatter chart, the power-density metric (dependent variable) is plotted against the motor power rating (independent variable). The minimum bound is conservatively estimated not to increase with power rating. A least-squares line is regressed through the data; this line expresses the most-likely value across all the power ratings.

2. The line parameters (slopes and intercepts) are then used to construct three parameters for the BetaPERT distribution as a function of motor power rating.[7]

3. The end product is a BetaPERT distribution, which is defined by a minimum, a maximum, and a most-likely value. We developed a

[7]The BetaPERT distribution effectively models expert opinions, and the three parameters it requires are a minimum value, most-likely value, and a maximum value.

separate distribution of the component's metric as a function of the component's power rating (i.e., size).

NDRI

Results from Applying Step 1 to Electric Ship Components

RAND

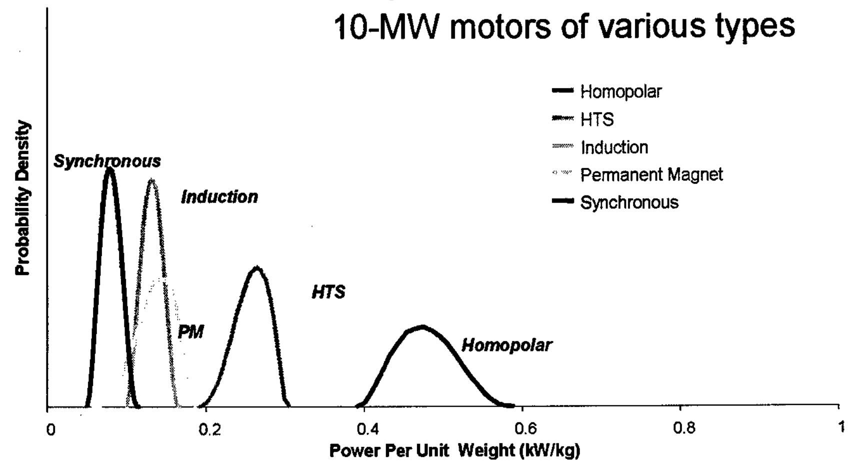
We gathered technical information on electric-drive ship components and assessed the collected data using probabilistic techniques. This section describes the results of applying step 1 to the collected data. Because the data are far from complete, we have not come to firm conclusions about the states of these component technologies. Nonetheless, the following general observations remain valid:

- Uncertainty in electric-drive component technologies depends on the power rating.
- The distribution of the performance of mature technologies is narrow across a range of a particular performance metric.
- The distribution of the performance of immature technologies is broad across a range of a particular performance metric.

Key Observation: Results Depend on Motor Power Rating

NDRI

Comparison of specific weight of 10-MW motors of various types



More mature technologies have narrower distributions

RAND

Above are the results for 1-MW motors, using the data and the methods we described previously for quantifying the uncertainty. For each of the five motor types, we determined a distribution to represent the uncertainty in achieving a specific weight (i.e., power per unit mass). The homopolar motor is one of the more-immature technologies; as a result, its performance (in terms of a particular metric, power per unit mass) is more uncertain than that of a more-mature motor technology, such as synchronous motor technology, which has been commercialized and exhibits a narrower peak in the chart above.

In general, higher-power-rated motors are less mature because few of them have been built. The exception is the synchronous motor, which is commercially available at ratings up to about 90 MW. One 19-MW advanced-induction motor has been built and tested recently, and 55 U.S. warships built before World War II had induction motors of about the same size but were technologically more primitive. For the other types, only small (<5 MW) models have been tested, if at all. The scalability of prototypes of certain advanced electric motors is thus uncertain.

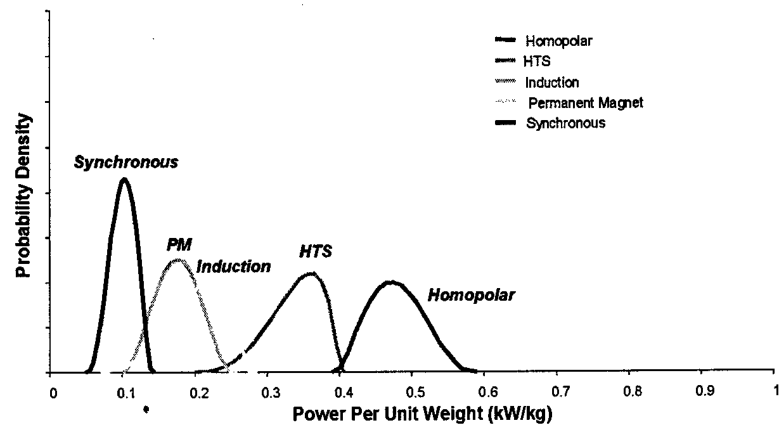
O'Rourke (2000), pp. 10–11, provided an assessment of the various motor technologies:

> The synchronous motor can be considered the most mature technology in application to large ships. There is consensus among both naval and industry sources that the synchronous motor, if scaled up to the higher horsepower ratings needed to move surface combatants and submarines at high speeds (i.e., 30+ knots), would be too large and heavy to be suitable for these ships .... The induction motor is generally considered the second-most mature motor type for application to large ships, after the synchronous motor .... Most of the sources consulted for this report argue (or do not contest) that it can be sufficiently power-dense to be suitable for use on U.S. Navy surface combatants .... The permanent magnet motor can be made quieter and significantly more power dense than the induction motor—enough so that it is consequently considered suitable for use on submarines as well as surface combatants .... The permanent magnet motor is less mature technologically than the induction motor, and consequently at this point may pose more development risk to incorporate into a nearer-term ship acquisition program .... The superconducting synchronous motor, if successfully developed, could be more power-dense and quieter than a permanent magnet motor. The superconducting synchronous motor is less mature technologically than the permanent magnet motor. The superconducting homopolar motor, if successfully developed, could similarly be more power-dense and quieter than a permanent magnet motor .... The homopolar motor, like the superconducting synchronous motor, is less mature technologically than the permanent magnet motor.

Observation: More-Mature Technologies Have Narrower Distributions

NDRI

Results for 20-MW motors

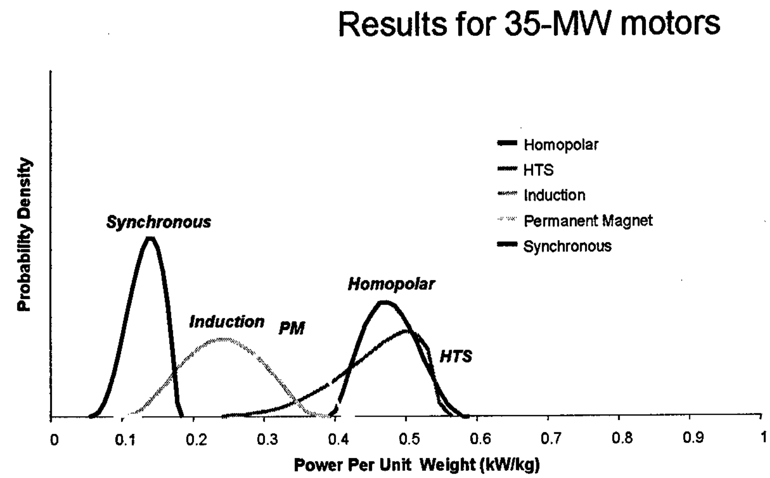


RAND

Both performance and uncertainty of motor technologies vary. This slide provides characterizations of 20-MW motor technologies. Examination of the probability density function allows analysis of the expected performance of each technology and also the uncertainty in the achievable performance. In general, more-mature technologies have narrower distributions. These distributions do not reflect all the uncertainty attributable to overcoming fundamental science or engineering questions or completing system integration.

Observation: Less-Mature Technologies Have Broader Distributions

NDRI

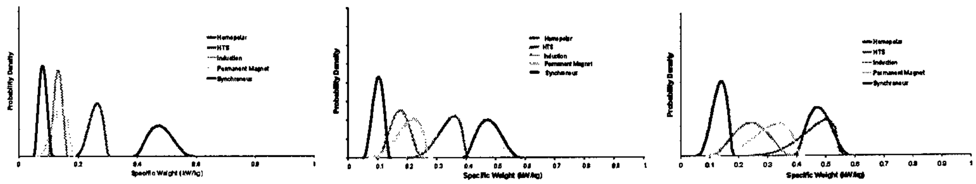


RAND

This slide characterizes 35-MW motor technologies. At these high power ratings, there is more performance overlap (i.e., specific weight).

Side-by-Side Comparisons Summarize Points

NDRI



(a) 10-MW Motor ***(b) 20-MW Motor*** ***(c) 35-MW Motor***

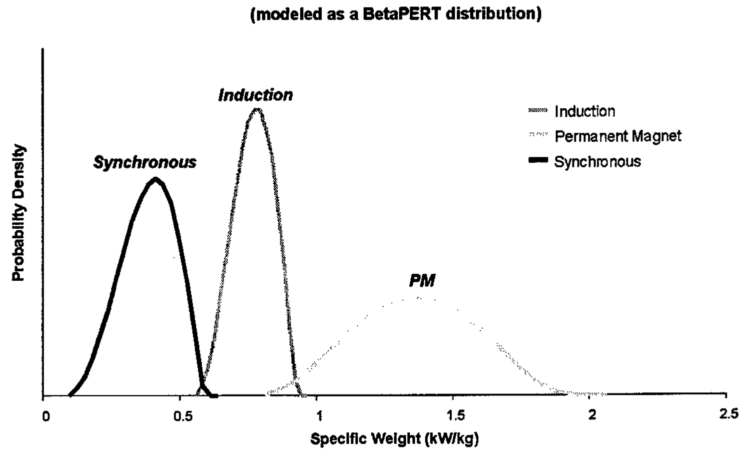
- **Motor technologies vary in both performance and uncertainty**
- **More-mature technologies have narrower distributions**
- **Less-mature technologies have broader distributions**

RAND

This slide summarizes the previous slides, which describe varying uncertainty associated with varying motor sizes and ratings. Note that motor technologies vary in both performance and uncertainty, depending on such factors as power rating (size); by definition, more-mature technologies have narrower distributions, and less-mature technologies have broader distributions

Results for 20-MW Generators Highlight Uncertain Potential of Certain Types of Generator Concepts

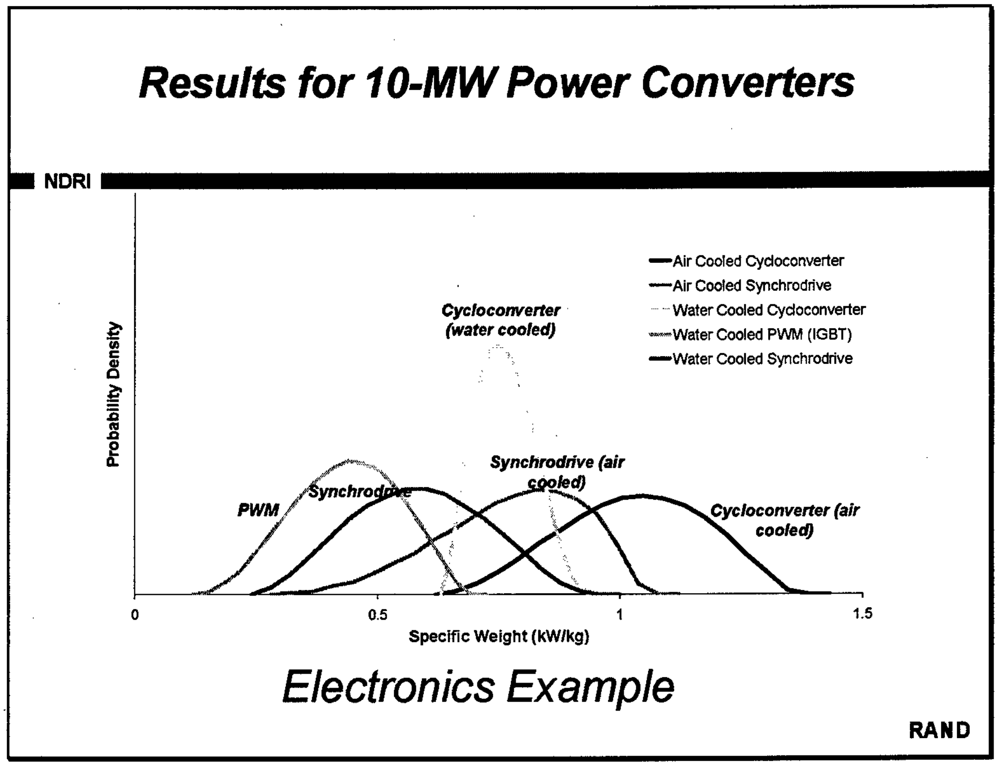
NDRI



Generator Example

RAND

The approach that earlier slides described is applicable to other technologies. This slide describes three types of generators: induction, permanent magnet, and synchronous. The technology types considered for electric motors are the same ones that can be used for generators.



This example uses the electronics as the component of interest and power per unit weight as the metric of interest. The following paragraphs describe these power electronic technologies.

For most alternating current (AC) electric motors, the frequency of the electrical current supplied to the motor must be manipulated to change the speed of the motor. This can be accomplished in a number of ways. Historically, the power electronic devices used to control certain electric motors are a cycloconverter, a synchroconverter (synchrodrive), or a pulse generator. The next several paragraphs explain how each operates. Controlling direct current (DC) electric motors, such as the homopolar motor, does not require any of the aforementioned devices.

The advantage of the *cycloconverter* is that it is a simple and compact system that converts an input voltage in a single step from one frequency to another. However, additional electrical filters are required to smooth the output. These filters add cost, weight, and volume.

The *synchroconverter* is a more complex, two step system. In the first step, the input current is converted from AC to DC; in the second step, the synchroconverter generates an output voltage at the desired frequency.

This type of power supply is also sometimes referred to as an *inverter.* Synchroconverter output can be poor, resulting in a noisy motor.

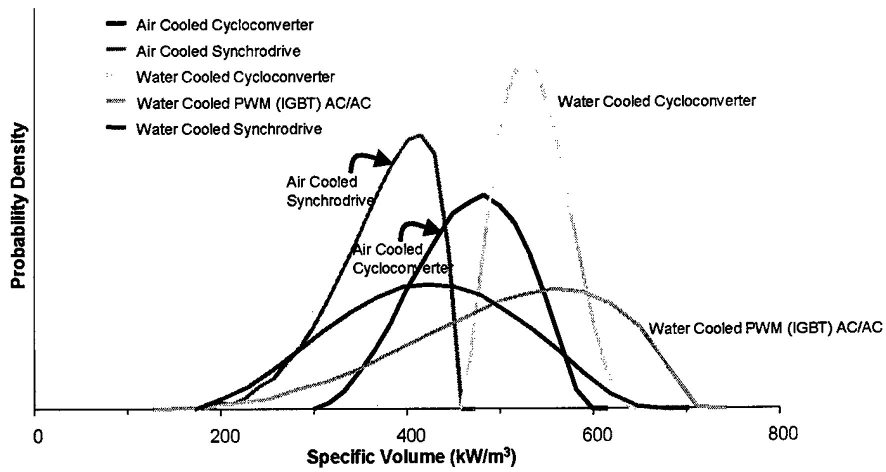
The *pulse generator* depends on the ability of the insulated gate bipolar transistor (IGBT) to turn on and off. Generating a number of pulses of varying widths creates a smoothly increasing and decreasing current in the stator. For a pulse-density-modulated input, a number of equal pulses generated at varying frequencies flows through the motor. At the windings, the amplitude of the current is proportional to the number of pulses that are generated within a given amount of time.

The advantage the pulse generator has over the synchroconverter is its ability to generate a current that better matches what the motor needs. The result is smoother operation because the rotation of the stator's magnetic field appears to the rotor to be smooth. The drawback the pulse generator has is that the IGBT can handle only relatively low voltages and currents. As a result, a large number of modules must be connected together in series to match the voltage requirements of the motor. Similarly, a number of modules must be connected in parallel to match the current requirements of the motor. As the performance of IGBTs improves, they may be able to handle higher voltage and current, so that fewer modules will be necessary to operate a large motor.

These power electronic devices require cooling systems. Air-cooled systems are less complex but also less compact. Water-cooled systems are more complex but also more compact. The next slide shows that water-cooled systems are more likely to be smaller than air-cooled systems.

Results for 10-MW Converters Indicate the Importance of Specific Volume

NDRI

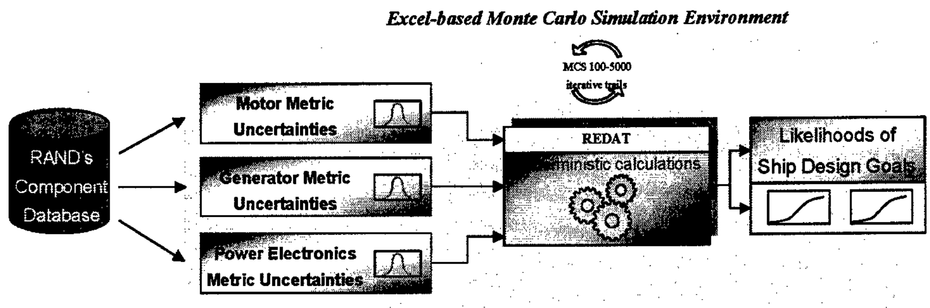


RAND

This example uses the electronics as the component of interest and power per unit volume as the metric of interest because the space the power electronics (represented by the ratio of power rating to volume occupied) occupy is more important than the mass of the power electronics.

2nd Step: Assess Ship Goal Uncertainties Given Component Uncertainties via Simulation

NDRI



RAND

The first step was to quantify uncertainty in component performance; the next is to integrate the performance of all components to address ship-level metrics. Simulation tools, such as REDAT, and Monte Carlo simulation tools facilitate this approach. The next section of this documented briefing discusses the framework for an analytical tool to quantify technological uncertainty for the whole ship.

NDRI

Results from Applying Step 2 to Ship Design Goals

RAND

This section describes results of applying step 2 to ship design goals. The results are based on the consideration of the metric, power per unit weight. Our main purpose here is to illustrate the type of analysis the framework facilitates.

We Considered Two Variants of Power Density as Metrics

NDRI

Two possible metrics:

- **Propulsion power/propulsion system weight**
  - **Power produced by prime movers divided by weight of propulsion components**
- **Nonpropulsion power/propulsion system weight**
  - **Power available after propulsion power needs are met**

RAND

We used the framework we have described to evaluate a couple of different ship-level metrics. The first simply takes the power from the ship prime movers and divides that by the weight of the propulsion components (Standard Work Breakdown Structure [SWBS] Group 200). The second considers the power that is available after propulsion needs are met. The framework incorporates the REDAT model and an Excel-based Monte Carlo simulation. The Monte Carlo simulator relies on REDAT to assess ship-level performance given the inputs, which are distributions of component-level performance. REDAT does include the effects of certain types of auxiliary equipment associated with such components as motors. It may require further enhancements to improve the way it quantifies the effects of the system voltages and currents that certain component technologies may require.

We Assumed an Appropriate Operating Profile

NDRI

The operating profile assumed in the REDAT model for the tests that follow (based on the ship-speed profiles in Appendix B) is as follows (assuming ~4,440 hours steaming under way):

Speed	Duration
8.0	13.9%
13.3	44.1%
17.8	25.5%
22.5	11.1%
28.4	5.5%

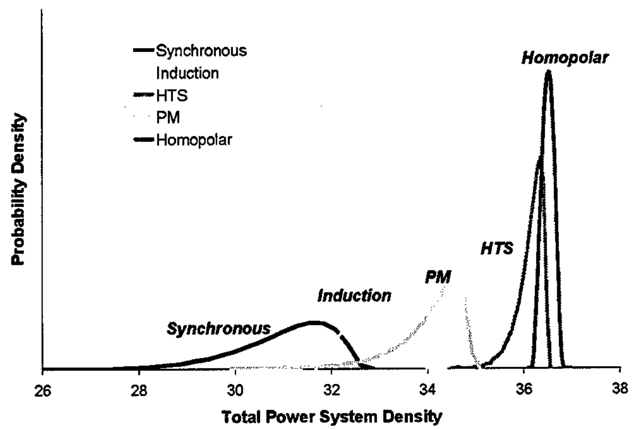
The operating profile specified here is used throughout this report with the exception of a few slides, which specify otherwise.

RAND

The operating profile assumed in the REDAT model for the tests that follow was based on the ship-speed profiles in the appendix.

Example Simulation Run: Propulsion Power Density Varied by Motor Type

NDRI



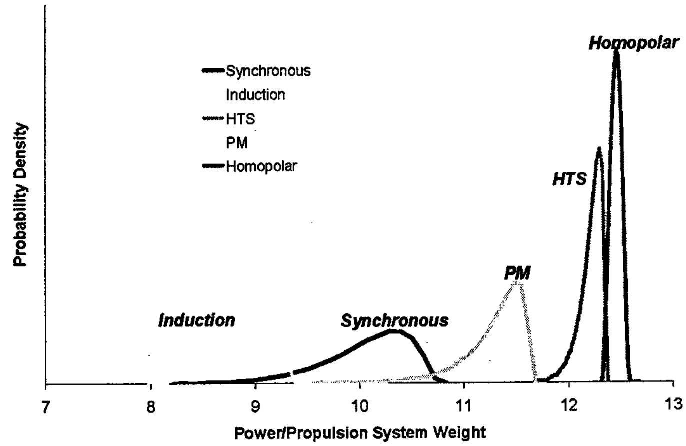
Example result: Synchronous motor is worse than induction motor (different from nonpropulsion power density)

RAND

This is an example analysis facilitated by the framework presented in earlier slides. The Monte Carlo simulator utilizes the REDAT model of ship design and calculates total ship power from the prime movers, as well as the weight of the propulsion system components (SWBS Group 200). The uncertainty quantified for each of the motor types with respect to the weight per unit power, in addition to other characteristics, translates into different estimates of overall ship power density. The synchronous motor type is understood to be larger and bulkier than the alternatives. As a result, it provides the least power-dense propulsion system for a ship. This example simulation is a successful sanity check because it confirms our intuition.

Example Simulation Run: Nonpropulsion Power Density Varies by Motor Type

NDRI



Example result: Using highly efficient motor technologies, such as the homopolar motor, yields more power for nonpropulsion needs

RAND

The same framework facilitated this example analysis. The Monte Carlo simulator again used the REDAT model of ship design and calculated the ship power available for power needs other than propulsion by considering the power from the prime movers and the power necessary to move the ship at the required speeds. Direct information on motor weight can come from collected data, and a tool like REDAT can add estimates for peripherals. The weight of the propulsion system components (SWBS Group 200) is also tabulated.

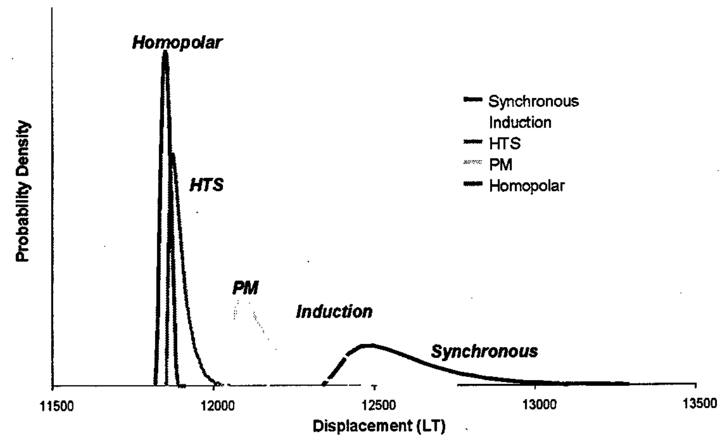
The uncertainty quantified for each of the motor types with respect to the weight per unit power, in addition to the given efficiency characteristics, translates into different estimates of overall ship nonpropulsion power density. Although the synchronous motor type is larger and bulkier than the alternatives, it generally fairs better than the induction motor, probably because the induction motor is less efficient.

A formal global sensitivity analysis would provide clearer quantitative information about the importance of individual inputs to REDAT. Such analyses estimate how the main input effects and interactions affect how output variability decomposes into components (Williams, 2002). We have

left this for future work. It should be noted that directly comparing motors would require additional or at least more-current data that may be proprietary. In addition, sensitivity analysis of specific component design details (e.g., system voltage, acoustic performance) would help rule in or rule out the need for additional modeling depth using such a tool as REDAT.

Example Simulation Run: Ship Displacement Varied by Motor Type

NDRI



Example result: Ship displacement is more sensitive to some motor types than others

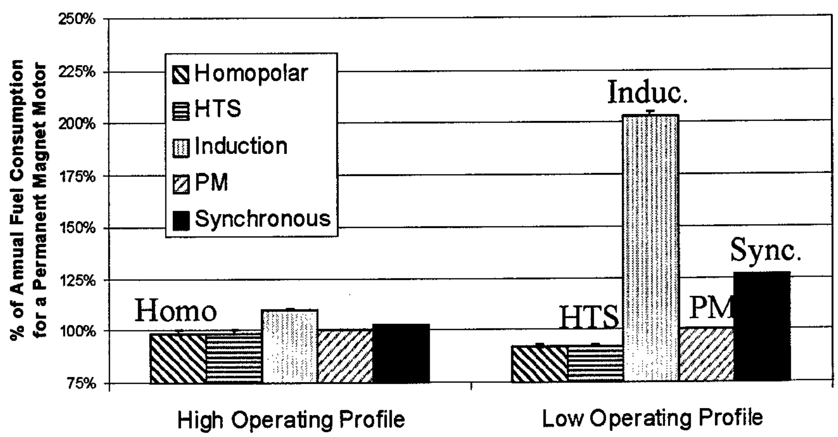
RAND

Ship displacement is more sensitive to certain motor types than to others. For the input distributions, variance reflects only uncertainty in the input variable. For the output distribution, the variance reflects both input uncertainty and the sensitivity of the system to changes in the input variable. As an example, the slide indicates that ship displacement was more certain for the homopolar motor than for the synchronous motor, even though power density is much more uncertain for homopolar technology than for synchronous motor technology.

For the policymaker, this result says that there are limits to how much improvements in a component characteristic (here, motor power density) can improve a ship measure (here, displacement). It should also be noted that this framework can be used to examine motor efficiency because an efficient motor translates into better fuel efficiency. This, in turn, means that it may be possible to use a smaller fuel tank, and thus means that the ship can be smaller.

Example Simulation Run: Fuel Consumption vs. Motor Types and Operating Profile

NDRI



Example result: Fuel consumption is sensitive to the motor type mainly for operating profiles that are dominated by low speeds

RAND

This slide presents values for annual fuel consumption as the motor type varies. For clarity, the performance of the induction motor, the HTS synchronous motor, and the homopolar motor are normalized against the permanent magnet motor such that the y-axis reflects the percentage difference between any motor and the permanent magnet motor's fuel consumption. Thus, the value for the permanent magnet motor is 100 percent.

While the magnitude of the estimates changes with changes in operating profiles, the order of technology performance does not. In all cases, homopolar motors consume the least fuel annually. The induction motor's performance is relatively poor in this figure at low speeds because its low-load efficiency is relatively poor.

Further analysis should be done on the interaction between the motor type and operating profile factors using more-formal methods. Turkey's multiple comparison method for contrasts or the method of Scheffe could provide simultaneous confidence intervals for differences in means (Williams, 2002).

Future Work

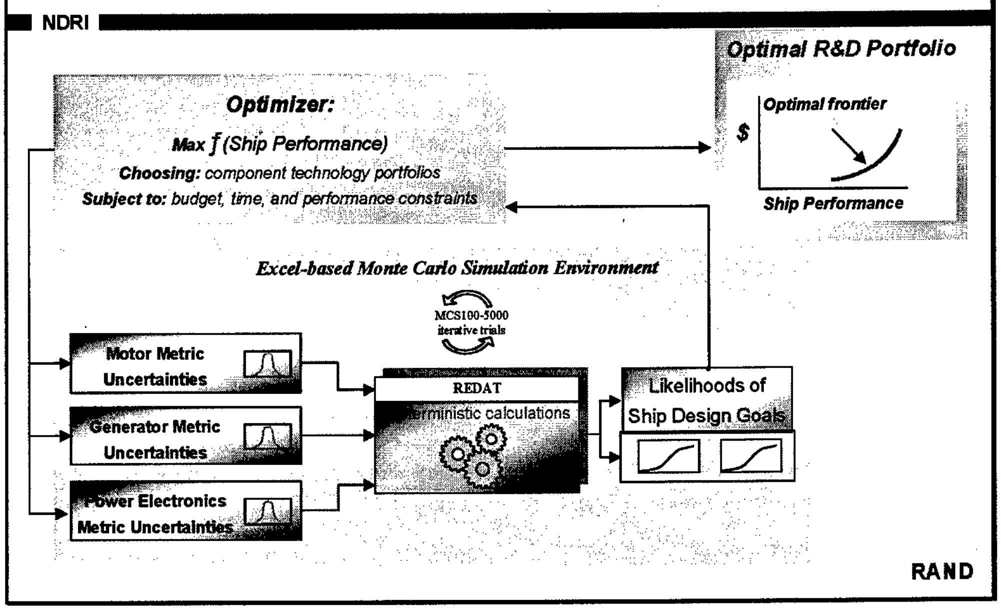
NDRI

Concepts for Using the Framework to Optimize an R&D Portfolio

RAND

This section describes a concept for using the framework to optimize an R&D portfolio. Using optimization algorithms to extend the multiattribute uncertainty analysis could help find the best solutions for maximizing performance, while minimizing cost, development time, and/or the probability that the research program might fail.

Base the Optimal Technology Mix on Ship Goals



Managing R&D is a classic problem of optimization under uncertainty. Laying an optimization framework over the previous uncertainty analysis allows decisionmakers to probe how different research management strategies might affect costs, performance, and schedule. The objective would be to optimize critical performance metrics, research costs, operations and maintenance costs, and research time requirements—the objective function. The relative importance of these factors is a policy decision, and multiobjective decision analysis can help decisionmakers understand the optimal frontier of technology choices.

Specifically, we envision a constrained optimization problem, in which the objective function is some measure of ship performance and the constraint functions involve research costs, operating and maintenance costs, and research time requirements, among other factors. For example, the objective function could be reduced to a single number (e.g., mean ship performance, variance in ship performance, coefficient of variation in ship performance). This approach would be suitable for determining component technology choices for a particular class of ships.

Multiobjective Analysis Incorporates Other Aspects of Uncertainty

NDRI

- **Research success is a multiobjective problem**
  - **Cost, time, and resources (physical and human) are important and uncertain factors**
- **Optimization and decision analysis can frame the problem**

RAND

Navy acquisition involves managing the development of complex systems. A multiobjective optimization approach could be useful for analyzing choices and quantifying the trade-offs. Research success is a multiobjective problem. Cost, time, and resources (physical and human) are important and uncertain factors.

Appendix A

NDRI

RAND Electric-Drive Assessment Tool (REDAT)

RAND

The type of analysis this documented briefing describes requires a good system model. RAND has developed a good tool for modeling electric-drive ships: REDAT. If the system model is computationally efficient, uncertainty analysis is possible using PC-based applications and relatively few computing resources. We have demonstrated this for analysis of electric-drive ships using REDAT and @RISK. This appendix provides some details on REDAT.

A Number of Analytical Tools Are Used to Develop a Framework Architecture

NDRI

- Database of component technologies from surveys
- Physics-based simulation program of ship performance: REDAT
- Microsoft Excel:
  - @RISK Monte Carlo simulation add-in
  - @RISK Optimizer
  - REDAT Excel-adapted, user-defined function

RAND

This slide lists the integrated analytical tools that make up the framework. They include (1) a database of data on components for the electric-drive concept, (2) REDAT (or other tools) to provide a mathematical model of a destroyer (or other hull shape) that deterministically translates point-estimate component performance metrics into quantitative ship-level performance metrics, and (3) Microsoft Excel to serve as the host environment for performing uncertainty studies taking advantage of the Monte Carlo simulation and the genetic algorithm add-in modules. REDAT was developed in C programming language and is interfaced to the Excel environment as a user-defined function via Visual Basic for Applications.

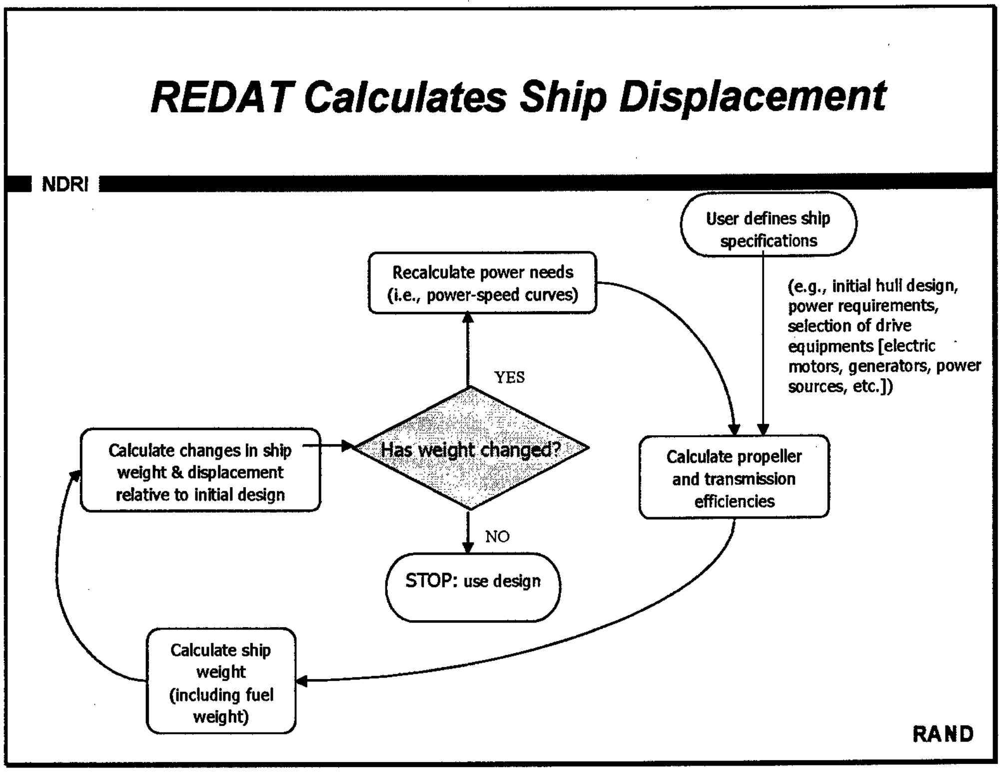
REDAT Derived from Past Research

NDRI

- **Software code initially developed and tested by graduate students of Prof A. D. Carmichael of MIT. See Ballard (1989) and Stantko (1992).**
- **Code modified and utilized at RAND to assess electric- drive destroyer designs**
  - Additional inputs incorporated
  - "Hard-coded" assumptions made to be variable (e.g., operating profile, motor specifications)

RAND

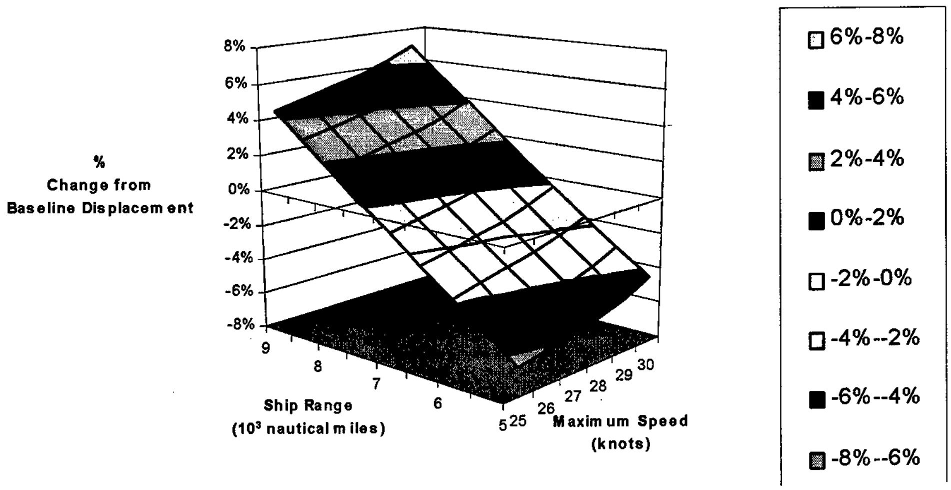
REDAT originated from the software development efforts of a Massachusetts Institute of Technology research group, to which RAND made modifications.



REDAT calculates ship displacement by considering endurance fuel weight and other factors. An initial displacement must be given as a baseline. (The examples in this report used an 11,700 LT destroyer as the baseline.) Then, the routine assesses the effects of changing equipment and fuel weight to recalculate displacement; reconsider resistance; and, subsequently, to determine endurance fuel needs. The program produces one final answer after the iterations have converged. REDAT also outputs estimates of quantities needed to calculate power densities, among other things.

Endurance Range and Maximum Speed Are Inputs to REDAT That Affect Displacement

NDRI



RAND

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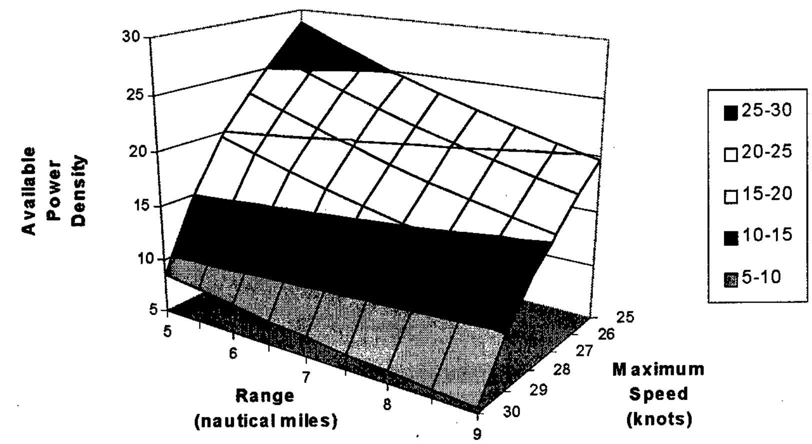
The REDAT model allows decisionmakers to assess easily the sensitivity of system performance to design parameters. For example, ship displacement can vary by as much as 12 percent across potential ship design ranges but only by 2 percent across variations in the design maximum speed. This form of analysis also allows users of the tool to understand potential trade-offs between system objectives.

As we noted earlier, global sensitivity analysis techniques can help quantify the main and interaction effects of the inputs to REDAT.

REDAT Captures the Effect of Maximum Speed as a Design Requirement

NDRI



RAND

REDAT can calculate the power available for nonpropulsion needs as a function of design parameters. This slide represents a sensitivity analysis for a DD-21 type destroyer as maximum speed and endurance range are varied (assuming four intercooled recouperated [ICR] gas turbines are on board). The units for power density are horsepower per long ton.

Appendix B

NDRI

Navy Ship Operating Speed Profiles

RAND

This report made assumptions about the operating profile of a Navy ship. This appendix briefly provides some background on operating profiles and makes the point that this variable is important and is determined by the ship's size, mission, area of operation, and other factors.

The Critical Elements of Ship Design That Affect Fuel Consumption

NDRI

Ship performance is a product of:

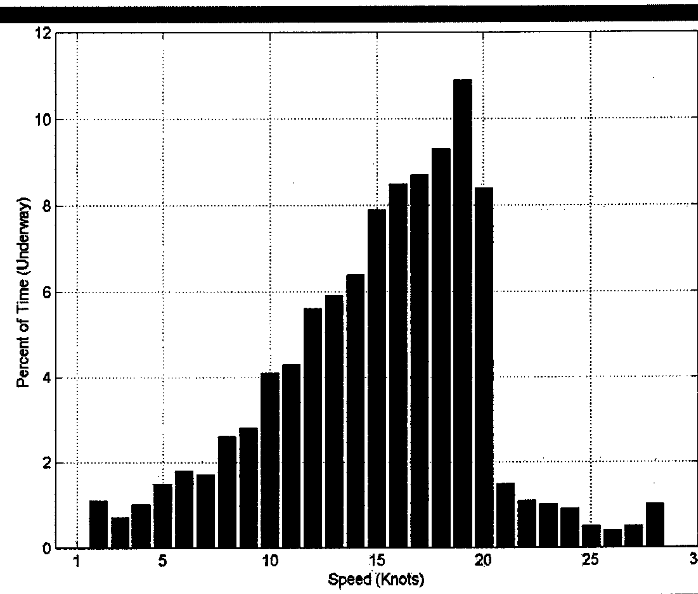
1. **Operating profile**
2. **Efficiency of the engines over the profile**
3. **Propulsor efficiency**
4. **Speed/power**
5. **Fouling**

RAND

The fuel efficiency of a ship is the product of many parameters. Five of them are listed above. The first factor, operating profile, is the focus in this appendix.

Operating Profile Must Be Assumed to Reflect Time Ship Spends at Achievable Speeds

NDRI



RAND

This chart shows the design operating profile for the DDG-51. The profile specifies the amount of time that the ship spends at particular speeds when it is under way.[8] A subsequent slide will show that the real-world operating profiles of destroyers may not include as much high-speed operation. Any ship model or simulation has to avoid considering only a narrow band of operating speeds. Thus, low-speed operation must be considered when determining the fuel load. The operating profile in this chart[9] was drafted at least 25 years ago (Brady, 1981). It has been suggested that its origin goes back to World War II operating profiles, which were dominated by high-speed, cross-ocean transits.

Further investigation of the history of operating profiles for Navy destroyers is outside the scope of this report. Peacetime profiles, as reflected in the data collected and reported in this briefing, are likely to be the best indicators and determinants for a 30-year life-cycle cost estimate.

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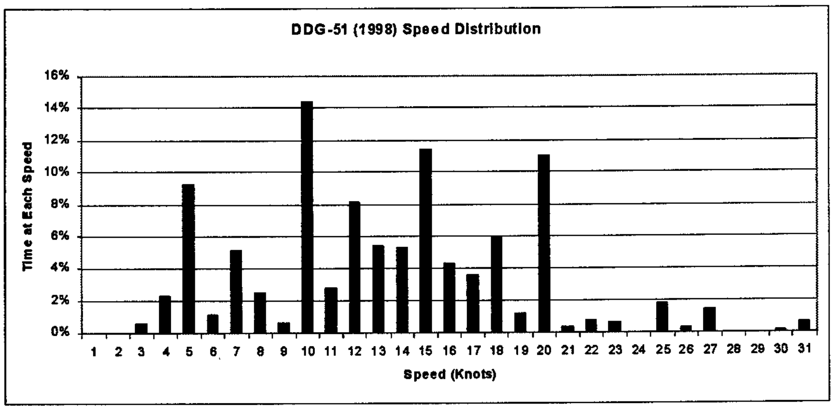
[8]Ships rarely operate at high power, and the Navy recognizes this by using design-operating profiles to select a ship's fuel capacity.

[9]See NAVSEA Code 614B, March 18, 1975.

Actual Data from 1998 Deployment of DDG-51 More Toward Lower to Middle Part of the Spectrum

NDRI

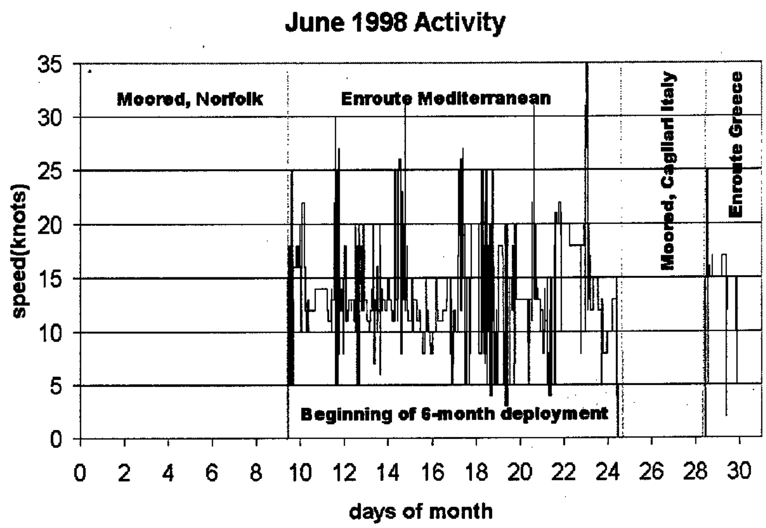


RAND

This slide shows the operating profile from an actual deployment of USS *Arleigh Burke* (DDG-51) in 1998, synthesized from data in the Naval Archives. Low-speed operation is still more prevalent than the design profile assumed. It is also interesting to note the significant amount of operating time at 5, 10, 15, and 20 knots.

Actual Data from 1998 Indicate Moment-to-Moment Speed Variations

NDRI

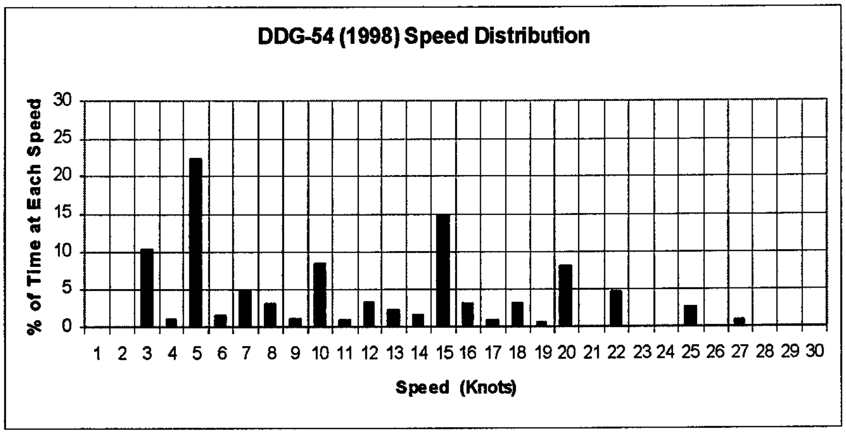


RAND

This slide shows the detailed speed changes that the average operating profile described in this appendix captures. The data are for the DDG-51's operations in June 1998. The chart was synthesized from data in the Naval Archives.

Actual Data from 1998 Deployment of DDG-54 Represent the Lower End of the Spectrum

NDRI



RAND

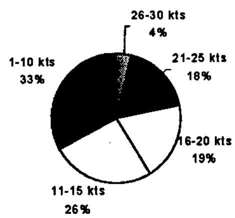
This chart shows an average operating profile for an actual deployment of the USS *Curtis Wilbur* (DDG-54) in 1998. The chart was synthesized from data in the Naval Archives. In this particular case, low-speed operation is prevalent. This is very different from the design profile shown earlier and shows that, in this case, the ship actually operated at lower average powers than her designers had anticipated.

The data in this slide show how operating profiles vary. Subsequent slides will show how different operating profiles incur different amounts of fuel consumption. Hence, the operating profile is a key variable in the ship's design and should be incorporated into analytic tools that explore design options and costs.

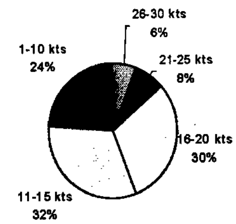
Simulated Performance of Destroyer Using Real-World Operating Profiles Shows Significant Fuel Consumption at Lower Speeds

NDRI

Fuel Consumed (LT)



Using DDG-54 Operating Profile



Using DDG-51 Operating Profile

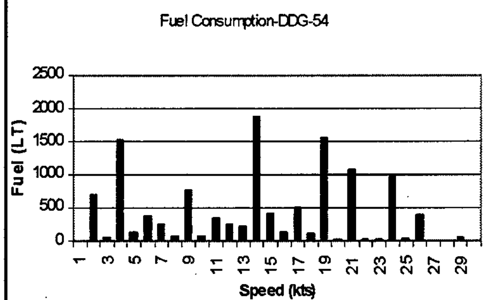
RAND

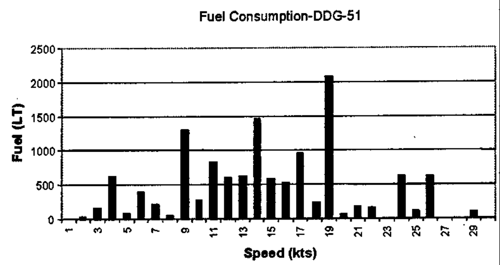
These pie charts show the results from the simulated performance of an electric-drive destroyer operating under the real-world profiles of the DDG-51 and the DDG-54 (1998) in the previous slides. The results show the projected fuel consumed over a single (simulated) year at different speeds. The inputs into the simulation were (1) ICR engines (two for cruise speed, four for maximum speed), (2) a fixed pitch propeller, (3) 4,440 hours of operation (annually), and (4) an electric-drive transmission.

Running the DDG-51 profile consumed approximately 12,860 long tons of fuel, and running the DDG-54 profile consumed approximately 11,940 long tons of fuel.

Simulated Performance of Destroyer Using Real-World Operating Profiles Shows Significant Fuel Consumption at Lower Speeds

NDRI



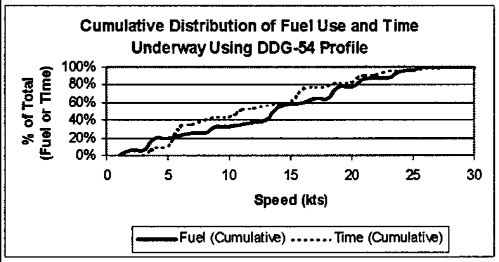


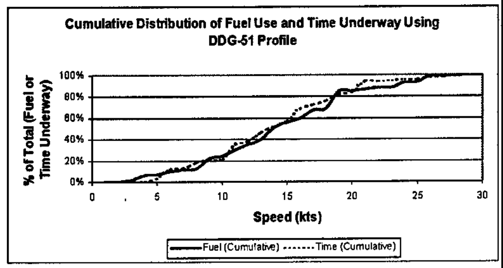
RAND

These bar charts show the same results from the simulated performance of an electric-drive destroyer operating under the real-world profiles for the DDG-51 and the DDG-54 (1998). We use bar charts to provide more detail on the fuel consumed at each speed.

Simulated Results with Real-World Operating Profiles (cont.)

NDRI





RAND

This slide shows the same results as in the previous two slides (that is, the simulated results of an electric-drive destroyer operating under real-world profiles). The results indicate that, in both cases, 60 percent of the annual fuel consumed would be burned at speeds at or below 15 knots. Similarly, in both cases, the majority of time spent under way is at or below 15 knots. Thus, fuel consumption at low speeds is an important factor that may be overlooked if peacetime operating profiles are not considered.

Recommendations About Operating Profile Data

NDRI

- **Important NOT to generalize operating profile details**
  - **Actual data regarding low speed operation cannot be ignored**
- **Potential designs will be affected by the choice of operating profile**

RAND

The data suggest that care should be taken to not generalize operating profiles; i.e., it is important to consider actual profiles as opposed to any continuous-form, notional specifications. The importance of low-speed operation—how key electric-drive components perform at low speeds assumed—is high.

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